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FERTILIZER PROBLEMS AND ANALYSIS OF SOILS IN CALIFORNIA

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IN BEGINNING THE DISCUSSION, it is useful to emphasize again the extreme complexity of the conditions which govern the growth of crops. The application of scientific methods to soil problems involves many difficulties not met with in the application of similar methods to industrial processes. Obviously, the latter can be controlled to a far greater degree than can the processes of plant growth as they occur under field conditions. Once the scientific and practical problems of a mechanical or chemical industry have been overcome, any given process may be repeated indefinitely with exactly predictable results. Such an achievement is seldom possible in the field of agriculture. Plants and soils exist in extraordinary variety, and both are subject to the variable and uncontrolled influence of climate. These statements would be true of any part of the world, but they have more than ordinary significance in California, because of its exceptional diversity of crops, soils, and climate. Notwithstanding the difficulties inherent in soil problems, real progress may be hoped for by persistent research, in field and laboratory, and only by this means.

CHEMICAL ELEMENTS OF THE SOIL ESSENTIAL TO PLANTS

The chief aspect of soil and plant relations to be dealt with in this circular concerns the processes by which crops take from the soil the mineral elements (plant foods) necessary for their growth.[2] The idea that only seven soil elements (potassium, phosphorus, calcium, magnesium, nitro-

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[2] These mineral elements are usually referred to as "plant foods," although this term is frequently used to designate only three elements, namely, potassium, phosphorus, and nitrogen. In an accurate sense, these elements are not foods, but part of the raw material by virtue of which plants synthesize the actual foods. Water and carbonic acid gas are the other raw materials. In the present discussion, the terms potassium and potash may be considered as equivalent; likewise calcium and lime, magnesium and magnesia.

gen, iron, and sulfur) are required by plants, is now known to be incorrect. The normal development of crops depends also on the ability of the soil to supply minute amounts of boron, manganese, copper, and zinc. Recent research conducted at the California Agricultural Experiment Station indicates that molybdenum is also an essential element. There are definite suggestions that minute quantities of still other chemical elements may be needed, but conclusive proof of their general essentiality has not yet been obtained. It is a reasonable assumption that boron, manganese, copper, and zinc or other elements required in only very small amounts, can usually be supplied by the soil without special treatment, and that additions to the soil would serve no useful purpose. Yet in the past decade, many reports have come from different parts of the world which indicate that certain previously obscure plant diseases may be prevented by applications to the soil, or directly to the plant, of these elements according to the nature of the disease. Of particular interest to agriculture in California, is the disease known as "little-leaf" or "rosette" of deciduous trees and as "mottle-leaf" of citrus trees. Zinc compounds have been found to be a specific corrective for this disease. A disease of trees sometimes given the name "exanthema" is often cured by the use of copper compounds. In humid regions, numerous cases of boron deficiency have been discovered and sometimes manganese is insufficiently available in the soil. The possibility is not excluded that for certain crops boron and manganese deficiencies exist in some California soils and preliminary indications of these deficiencies have been obtained in several field or greenhouse experiments.

Along with the development of knowledge of the functions in plant growth of elements like the four mentioned have arisen suggestions that the presence of these elements as impurities in commercial fertilizers, may be of consequence in making a choice of a particular type of fertilizer. But it should always be kept in mind first, that the application of these elements is needed only for special crop and soil conditions; and second, that when they are needed the quantities added as impurities in a commercial fertilizer may be wholly ineffective for California soils with their generally high power of fixation. For example, from several hundred to several thousand pounds of zinc sulfate per acre may be required as a soil treatment to correct a little-leaf condition, and in practice zinc applications are often made directly to the tree.

While some very small concentration of boron in the soil solution is essential for plant growth, this element can also become highly toxic to plants when concentrations rise—even though the toxic concentrations are still relatively low. However, great differences in tolerance to boron

exist among different species of plants. The practical problem of excessive content of boron in certain irrigation waters has been given much study in California.

THE SOIL AS A NUTRIENT MEDIUM FOR CROPS

The prevailing theories of plant nutrition are based on the assumption that plants can take up mineral nutrients only after the latter are dissolved in the soil moisture; and clearly the soil solution is a major immediate source of these nutrients. The nitrate, for example, is nearly all present in the soil solution. Since the publication of the last edition of this circular, however, evidence has become available that an additional mechanism may be effective for the absorption by the plant of those mineral nutrients that can be held by the soil colloids. According to the recently developed theory, nutrients so held may move directly into the root through a colloidal system when the soil colloid is in intimate contact with the surface of the root. This movement involves an interchange of ions[3] between the root and the colloidal particle of the soil, without the intervention of a soil solution in the usual sense of this term. To elaborate the new point of view would require much technical discussion, and this is unnecessary for the purposes of the present circular, since most of the practical deductions based on the theory of the soil solution remain sound, even though consideration of an additional mechanism of intake of certain nutrients by the root is now justified.

It is seldom true that there are present at any one time in the soil moisture sufficient amounts of all mineral nutrients needed by plants during the whole period of their growth. For example, during the season a crop may remove from the soil many times the amount of phosphate present in the soil moisture at the beginning of the season, even on the basis of the maximum volume of soil in which roots can develop. As far as absorption of nutrients from the soil solution is concerned, availability becomes then a question of the rates and concentrations at which essential elements contained in the solid portion of the soil can dissolve in the soil moisture. These rates and concentrations should be adequate to keep pace with the rates of intake by the plant, to the extent that no limitation in growth will occur because of a shortage in any one of the essential elements. A deficiency of one element will limit growth even if all other elements are present in abundance.

The solution of certain mineral elements necessary to plant growth

[3] When a salt is dissolved in water, it is said to dissociate, that is, to form electrically charged ions. For example, potassium sulfate would form positively charged potassium ions and negatively charged sulfate ions. A positively charged ion is termed a cation, and a negatively charged ion an anion.

depends primarily upon the production of acids in the soil, which in turn is dependent upon biological activities, that is, the activities of microörganisms and of root cells. The most important acids produced in this way are nitric, sulfuric, and carbonic. In most California soils these acids are neutralized by basic substances in the soil as fast as they come into existence. The salts thus formed dissolve in the soil moisture and become part of the nutrient medium of plants. To illustrate, bacterial action may bring about the production of nitrate (derived originally from nitrogen present in the organic matter of the soil), a soluble and available form of nitrogen; and at the same time calcium, magnesium, or potassium will go into solution and become available to plants. Since these activities of microörganisms are primarily dependent upon the presence of organic matter in the soil, it is evident that organic matter has a function in the solution of the elements named above. It is still uncertain whether this particular action of organic matter is indispensable in view of the direct action of root cells described in the next paragraph. In the case of phosphate and iron, organic matter may have a useful solvent effect in some soils. The great value of organic matter in the soil for other reasons, especially improvement of physical condition of the soil and providing a reserve of nitrogen, has been discussed on many occasions and this point need not be elaborated here except to emphasize that if *for any reason* organic matter promotes the growth of root systems, the absorption of mineral elements will be accelerated, and in that sense availability increased.

The second means by which acids are formed in the soil is the excretion of carbonic acid by roots. The general opinion is that no other acid is excreted by roots, but this opinion is not necessarily conclusive in its application to all plants and to all conditions. In any event, the carbonic acid excretion by roots is considered by most investigators to be of great importance, because of the very intimate contact between fine roots, or root hairs, and colloidal soil particles. The dissolving of minerals, or some of their components, can in this way take place in the closest possible proximity to the absorbing root surfaces. In addition to direct-contact phenomena there is afforded, therefore, an especially favorable opportunity for the plant to have access to the mineral particles of the soil. The hydrogen ions of the acid can readily displace potassium, calcium, magnesium, and sodium from mineral or organic complexes of the soil, capable of base exchange.

THE ABSORPTION OF ESSENTIAL ELEMENTS BY ROOTS

As suggested above, the total area of root surface capable of absorbing mineral elements may determine in part the ability of a plant to obtain from the soil adequate quantities of essential mineral elements. The plant is affected not only by the kind of soil it grows in but also by the amount of soil available to it. For this reason, as well as because of the water relations involved, emphasis is placed on maintaining conditions in the soil favorable for root growth. Among these conditions, suitable aeration and prevention of the formation of impermeable layers are often extremely important. Irrigation and cultivation practices are definitely related to the mineral nutrition of plants. Toxic substances, organic or inorganic, and injurious microörganisms interfere with normal absorption by roots. Furthermore, the growth of roots is influenced not by soil conditions alone, but also by the environment of the top of the plant, where the food and growth substances necessary for root growth are manufactured. Root growth and activity, and consequently the ability of plants to obtain essential elements from the soil, may be modified by climatic conditions, fruit production, plant disease, insect injury, and other factors.

The roots of plants do not take up the soil solution simply as it exists in the soil. Mineral elements may be removed at a faster or slower rate than the water in which these elements are dissolved. The plant should not be likened to a lamp wick sucking up the soil solution. *Roots perform their functions normally only as a result of the activities of healthy living cells, which require a suitable supply of oxygen.*

Different nutrients may be removed from solution at very different rates. Plants, therefore, have a "selective" action; but this does not mean that they possess the power to select only those substances required for their growth, rejecting all else. On the contrary, injurious substances may often be taken up by plants when they are present in the soil, and essential elements are absorbed sometimes in quantities far greater than those needed for plant growth.

AVAILABILITY OF POTASSIUM AND PHOSPHATE

Assuming that the production of acids by microörganisms or by plant roots proceeds at a satisfactory rate, is it certain that potassium and phosphate will enter the root at the rates necessary for satisfactory crop growth? This depends upon the nature and status of the mineral and organic compounds containing potassium or phosphate. The colloidal part of the soil is especially important in determining whether or not a

soil can supply to a plant adequate amounts of potassium or phosphate.

First giving attention to the question of potassium, it is found that the amount of potassium easily dissolved by fairly dilute acids (such as 0.25 per cent nitric acid) comprises only a small fraction of the total amount of potassium contained in the soil. The supply of this more easily dissolved potassium has an important bearing on the concentration of potassium capable of being maintained in the soil moisture, although the relation is not a simple one. In general, it may be said that the capacity of potassium to dissolve in the soil moisture is much more important than the total percentage of potassium present in the soil; but a high percentage may not be without significance if it implies a greater number of contacts between root surfaces and potassium minerals. The fineness of division and the chemical structure of such minerals is important in this connection, as well as the physiological character of the plant.

Experiments with a considerable number of California soils, carried on in Berkeley over a long period, show that continuous cropping reduces the supply of available potassium, as determined by methods of the type described in the above paragraph. In some soils the amount of the reduction is of the same magnitude as that of the total potassium removed from the land by the crop.

If a soil becomes depleted in the easily soluble forms of potassium, plants will have a relatively less favorable medium from which to absorb this element. But it does not necessarily follow that crops will always make unsatisfactory growth when the more soluble types of potassium are exhausted. Some crops may still find it possible to take out of the soil adequate amounts of this element for an indefinite period of time. If the plant roots have a sufficiently large area of actively absorbing root surface, and if the growth cycle of the plant gives adequate time for absorption, a suitable adjustment may take place, even in soils which never contain in their soil moisture more than a slight concentration of potassium. Of course if the potassium supplying power of the soil falls too low, then plants will fail to thrive without proper fertilization of the soil with potassium.

In some of the humid regions of the world, extreme deficiencies of available potassium in the soil occur frequently; but they are not common in California, although certain types of soil are now definitely recognized to be low in available potassium.

There is the additional very important idea to be considered, that different kinds of plants may differ in respect to the amounts of potassium required for their type of growth. Most agriculturists believe that plants producing large amounts of starch or sugar have a high potassium

requirement, although the function of potassium in plant growth is by no means fully understood as yet. Such plants are considered to give the most satisfactory yields on soils containing relatively large amounts of potassium in easily soluble form. These ideas are chiefly based on experience in other parts of the world. It is not yet known whether or not crops of the type referred to would respond to potassium fertilization when grown on the majority of California soils. In a few cases the evidence is positive, and in others negative. At this point, it should be noted that many experiments indicate that it is possible to increase the percentage of potassium present in a plant by increasing the amount of available potassium in the soil through fertilizer additions, unless the soil can already supply all the potassium the plant can absorb. The increased amount of potassium contained in the crop, beyond a certain percentage, would be superfluous in that it would lead to no increase in growth or improvement of quality. Such excess absorption of an element is sometimes termed a "luxury consumption." The amount of potassium required by a crop may vary according to climatic conditions. Certain field experiments in Europe and studies on plants grown under controlled conditions in California, and elsewhere, suggest that the potassium requirements of plants are altered by changes in light or temperature. The requirement by fruit trees will vary with heaviness of bearing. The importance of age of tree and of climatic environment in relation to the amount of fruit borne by the tree is illustrated by studies on the prune "dieback" disease.

The total amounts of phosphorus present in ordinary soils are far smaller than the total amounts of potassium, but analogous considerations in regard to solubility apply. To give an illustration of extreme conditions: two California soils were compared, each containing approximately the same total amount of phosphorus. Practically no phosphorus was dissolved from one soil by a relatively weak acid; while from the other soil, treated in exactly the same way, more than half of the total phosphorus was dissolved. Many plants of agricultural interest make very poor growth in the first-mentioned soil because of lack of available phosphorus; while in the second soil there is no deficiency of this element.

The question of phosphate availability is, however, much more complex than the simple illustration just given would imply. New evidence[4] gives a basis for dividing the phosphate of the soil into two classes; that which dissolves in acid and that which does not dissolve in acid but which is released into alkaline solutions, as a result of anion exchange, from

[4] For further discussion see: Burd, John S., and H. F. Murphy. The use of chemical data in prognosis of phosphate deficiency in soils. Hilgardia 12(5):323–40. 1939.

soil colloids. The availability to plants of phosphate held by the colloid depends upon the degree of saturation of the colloid with phosphate, as well as upon the total amount of phosphate held in this way. The nearer the colloid approaches complete saturation with phosphate, the greater the availability of phosphate will be. In many soil systems the availability of phosphate is associated with the buffering capacity of the soil (ability to resist lowering of pH by acid). If this is high the plant may be prevented from acquiring potentially acid-soluble phosphate. Thus phosphate may be relatively unavailable in a soil containing a large amount of lime.

The discussion of phosphate availability requires consideration not only of the chemistry of the soil but also of the biological factors involved. Different kinds of plants vary immensely in their power to secure adequate amounts of phosphate from soils of low phosphate availability. The extent of surface of the root system and the length of the season for acquisition of the plant's phosphate supply may explain in part the divergent responses to phosphate fertilization of different types of plants growing in the same soil. One possible partial explanation of the special ability of certain species of plants to obtain phosphate tightly held in colloidal combination is that the roots excrete organic acids, some of which are known to have the power to displace phosphate adsorbed by soil colloids. Fruit trees offer one example of crops capable of obtaining enough phosphate from soils of extremely low phosphate availability—soils in which most annual crops might fail for lack of phosphate.

It is hoped that this discussion, although very incomplete, will nevertheless make it clear how complex the question of availability of potassium and phosphate is. Attention must be given, not only to the soil type, but also to the type of crop, to conditions in the soil favoring or inhibiting root growth, to the organic-matter content of the soil, and to climatic environment.

USE OF NITROGEN AND OTHER FERTILIZERS

Having sketched a few important general relations existing between crops and soils, certain views concerning fertilization will now be considered. In the first place, it is important to realize that some type of fertilization is required, sooner or later, for most crops under modern agricultural conditions. If we take a general average of experience throughout the world, we find that special concern is felt about maintaining available nitrogen in the soil, although in many regions when the cropping system includes legumes, phosphate is the dominant need. Crop responses to nitrogen applications, although not universal, are met

with under the greatest possible variety of soil, crop, and climatic conditions. The nitrogen requirements of many crops are very high.

Nitrogen is an element which can easily be lost from soils. When it is in the form of nitrate it is subject to leaching. But it is also possible to lose nitrogen in gaseous form. In this connection experiments made in Berkeley are of interest. Thirteen soils, from different parts of California, were studied over a period of many years with reference to their total content of nitrogen. The soils were placed in a series of large containers, and one lot of each soil was cropped with barley annually. The straw was not returned to the soil. At first the soils were maintained in a moist condition continuously, but without excess moisture or leaching. Under these conditions, in the course of five years, an important proportion of the total nitrogen in the soil was lost.[5] The losses from the cropped soils resulting from the activities of microörganisms were much greater than the losses of nitrogen in the crop removed. After a period of cropping, the soils referred to reached a low level of crop production, and the total nitrogen in the soil changed only slightly from year to year. The large losses of nitrogen occurred during the earlier years of the experiment, when nitrate production was high. The equilibrium content of nitrogen and of total organic matter in a soil depends on climatic conditions. When sufficient moisture and oxygen are present in the soil and soil temperatures are high, oxidation of added organic matter occurs with great rapidity. This is true under many of the soil and climatic conditions of California.

Much further work must be accomplished before the nitrogen economy of the soil is sufficiently understood, but it is evident that losses of nitrogen may be great under some circumstances.

This fact may help to explain why nitrogen additions to the soil are so frequently beneficial, whether accomplished by the growth of legumes or by the use of animal manure or commercial forms of nitrogen. With all questions relating to nitrogen, it is of the utmost importance to consider the activities of the soil microörganisms and the possible influence of irrigation and cultivation practices and additions of organic matter on these activities. An excess of carbohydrate material leads to a temporary loss of available nitrogen (nitrate), which is utilized by microorganisms when their rapid multiplication is made possible by the energy of the carbohydrate.

To understand correctly the fertilization of a soil with phosphate or potassium requires recognition of the fact that these substances react chemically with the soil. *The point of interest, as far as crop growth is*

[5] Later in the experiment the soils were kept moist only during the cropping season.

concerned, is the resultant condition of the soil after fertilizers or other amendments are added. The same fertilizer will produce different effects, in greater or lesser degree, in every different soil. Sometimes reference is made to the use of "balanced fertilizers." The balance that is important is not in the fertilizers, but in the soil after the fertilizer has been added and has reacted with the soil. A fertilizer cannot, in any accurate sense, be compared with a "balanced ration" for an animal. The feeding of animals and the absorbing of mineral elements by plants are entirely different in nature.

Potassium (potash) reacts in soils chiefly with certain colloidal substances, which are in certain respects analogous to artificial zeolites such as are used in softening water. In this reaction there occurs an "exchange of bases." For example, some of the potassium added may go out of solution and calcium (lime) or magnesium (magnesia) enter into solution to take the place of the potassium which is "fixed." Generally, in soils of fairly heavy character, nearly all of the potassium added in an ordinary fertilizer application is fixed in this way, liberating other bases, especially calcium and magnesium.[6] In some soils potassium may also be fixed by an irreversible exchange process so firmly that it becomes relatively unavailable to plants.

The phenomenon referred to above is of great interest in connection with the fertilization of fruit trees under California conditions, for the reason that in many soils most of the potassium added may be fixed in a surface zone, out of reach of the major part of the absorbing root system. Therefore, in soils of high fixing power it is especially difficult, or even economically impossible, to alter the condition of the soil in contact with the roots developed very far below the surface zone. Recently, however, a few positive results of potash fertilization of prune trees have been reported, with potash fertilizers applied below the surface zone of soil.

Although the fixation of potassium may prevent this element from becoming available to roots in the deeper layers of the soil, nevertheless, in many soils the "fixed" potassium can be absorbed by plants to a large extent, when roots develop directly in contact with the soil particles on which the fixation occurs. This is true of certain California soils of high fixing power for potassium, in experiments with plants such as wheat, barley, tomatoes, and beets. The fixation of potassium in such cases is not so firm as to prevent it from being absorbed by the plant at the zones of contact between roots and soil particles. The plant is an active agent in

[6] Nitrogen in the form of ammonia nitrogen is also at first fixed in a similar manner, but later nitrification takes place and the nitrate readily moves downward. Thus availability to the plant is only temporarily influenced by the fixation.

the process, because of carbonic or other acids which may be excreted by roots (producing hydrogen ions to exchange for potassium ions), and because of the rapid removal of potassium from the soil moisture by the growing plant. The latter action makes it possible for new supplies of potassium to enter into solution continuously as long as a suitable source of potassium remains in the solid portion of the soil. The previous discussion of root-soil colloid contact phenomena should also be recalled at this point. It is clear from all these considerations that the location and rate of growth of root systems is a very important question in fertilization.

Phosphate, as well as potassium, when added to a soil will undergo chemical change, although the chemical reactions involved are different from those applying to potassium. Phosphate easily soluble in water before addition to the soil usually becomes much less soluble afterwards. Consequently, in most soils it is very difficult to change the soil condition very far below the zone in which the phosphate fertilizer is mixed with the soil. Some penetration may at times be obtained by use of unusually large amounts of fertilizer, by effects of organic matter, or by special methods of application.

Just as with potassium, the fixation of phosphate may not prevent plants from absorbing at least some of the phosphate added in a fertilizer, provided again, that sufficient root development occurs in that portion of the soil to which the phosphate is added, or to which it penetrates. A striking example of this is found in certain California soils of high fixing power, in which some crops make hardly any growth because of the insolubility of the phosphate naturally present. Yet the addition of certain soluble phosphates to these particular soils has an extremely beneficial effect on various surface-rooted crops. The manner in which plant roots absorb phosphate in such cases is only very slightly understood as yet; but no doubt stress can be placed on the intimate contact between roots and soil particles, and on the finely divided and reactive nature of the compounds formed when added phosphate is freshly precipitated in the soil. With certain methods of application, there may occur direct contacts between roots and particles of soil saturated with phosphate, or even still unchanged particles of some types of phosphate fertilizer. The proper placement of the phosphate by localized application to the soil is often the key to successful fertilization.

There is evidence, however, that it is possible for a part, and sometimes a major part, of the added phosphate to undergo such strong fixation that it becomes unavailable to plants, even when root contact takes place. This loss of availability may be more rapid with some forms of phosphate than with others. These remarks do not apply with equal force

to all types of soil, and, furthermore, the method of applying the phosphate fertilizer modifies any comparisons of different types of phosphate fertilizers. As stated above, potassium, when added to certain soils, also may undergo changes rendering it unavailable to plants or available only with difficulty, notwithstanding proper contacts between soil and roots. In the California soils investigated, it does not appear that added potassium can become unavailable to nearly the same extent as phosphate does in certain types of soil.

From the foregoing consideration, it is evident that when crops are not too deep-rooted, it is possible to modify, at least for a time, the nutrient condition of a soil with respect to phosphate and potassium by the use of suitable fertilizers, applied in reasonable amounts. But the practical question arises as to how generally phosphate and potassium, as well as nitrogen, can be used profitably. Concerning this point no general statement can be made. The kind of soil, its previous agricultural history, the amount of potassium or phosphate already removed by crops, the crop to be grown, and the climate, all enter into the equation. Many soils may maintain their productivity for a long period with the addition of only one or two of the three above-named elements, for the reason that the remaining elements are still supplied in sufficient abundance from the reserve already present in the soil. A balanced condition for crop growth might be brought about in a soil by the simple addition of nitrogen, and perhaps organic matter, in appropriate form.

These conclusions are in no way inconsistent with recognition of the fact that continuous and intensive cropping in general tends to lower the amount of easily dissolved phosphate or potassium, even in soils of high initial fertility, such as are often found in this state. The question which has to be asked for each soil is: Has a critical point been reached, or will it be reached soon, or is a state of depletion still far in the future? The answer to this question will be modified in accordance with the nature of the crop as well as the soil; for, as already indicated, some crops, under otherwise favorable conditions, may be able to absorb sufficient potassium or phosphate from slightly soluble compounds, often considered unavailable. These are present in most soils in amounts that are very large relative to crop withdrawals. In numerous California soils, potassium regarded by the soil chemists as "nonreplaceable" by chemical agents may nevertheless be available to crops.

Not infrequently sulfur may be deficient in a soil; this has been found true of a number of California soils on which leguminous crops are grown. In humid regions magnesium deficiencies have been noted in some soils, especially those of sandy character.

However these questions may be decided for particular cases, the general statement can be made that serious soil difficulties will arise in course of time under conditions of exhaustive cropping, unless provision is made for additions to the soil, whether by means of covercrops, animal manure, nitrogen fertilizers, or other commercial fertilizers, or by some combination of these materials. The chemical, physical, and biological state of the soil are all involved. The maintenance of productivity will not be automatic, although certain California soils seem to be initially so well supplied with available nutrients that development of marked deficiencies may be long delayed.

COVERCROPS AND ROTATION OF CROPS

The turning under of covercrops may tend to build up the soil reserve of easily available potassium and phosphate. Aside from effects of organic matter already discussed, this action is explained by the gradual accumulation in the growing plants of phosphate and potassium derived from very slightly soluble compounds present in the soil, including the deeper zones of the soil. The entire amounts accumulated in the plant tissues, when returned to the upper part of the soil, may remain in an easily available form for other crops. How important these changes are in California soils is not yet known. Plants grown on soils containing very small amounts of available potassium or phosphate are likely to have relatively low percentages of these elements present in their tissues. Consequently, there would be this limitation to the possible increase in availability of potassium and phosphate through the use of covercrops. Also the power of some soils to fix potassium or phosphate in more or less unavailable form tends to limit the building up of a supply of available nutrients. Covercrops, however, may have great importance for reasons other than those related to availability of phosphate or potassium. It is particularly necessary to stress the effects of organic matter and of growing roots on the penetration of water and on aeration.

In many parts of the world of longer agricultural experience, it has been found that the practice of continuously growing one crop often gives very unfavorable results. In such cases, suitable rotations of crops, including legumes, frequently accompanied by the use of phosphate or other fertilizers, have been worked out through long periods of field experience. The desirability of crop rotation is not necessarily to be ascribed merely to the maintenance of nitrogen content in the soil, or possible differences in the abilities of different crops to utilize relatively insoluble potassium or phosphate, however important these factors may be. Some investigators emphasize the development of injurious soil

microörganisms, plant diseases, or toxicity caused by residues of crops. There are cases in which it has been possible to grow the same crop successfully for many years, when animal manure, or commercial fertilizers, or both, have been applied in suitable amounts; but it appears that in general, rotation of crops, if feasible, is sound practice.

USE OF ANIMAL MANURE

In considering the matter of potassium or phosphate fertilization, it is essential to recall that considerable quantities of these nutrients, and especially of potassium, are added to the soil when large amounts of animal manure are systematically applied. From earliest times, the observation has been made that the use of animal manure nearly always produces highly favorable effects on the growth of plants. This question has been under careful study at the Rothamsted Experimental Station, England, for over 80 years. It has been found that farmyard manure applied at the rate of 14 tons per acre annually now gives higher yields of wheat than do artificial fertilizers containing similar amounts of nutrients. From these, and from many other experiments and observations, it appears that the beneficial effects of manure are not always limited to its content of nutrient elements, at least of those usually emphasized. The possible improvement of the physical condition of the soil is desirable and the modification of the soil as a medium for beneficial microörganisms must be given consideration. Other beneficial effects may be brought about which are not clearly understood at the present time.

One suggestion from recent research is that manure, and other organic matter, may contain organic substances essential for plant growth in minute amounts. Substances of this kind are, of course, synthesized by the plant itself; but this synthesis is conceivably not always adequate for the maximum growth permitted by other factors of the environment. The general importance of externally derived growth substances cannot be appraised at the present time.

Although the use of manure may largely solve a problem of soil fertility for certain crops or districts, it is obvious that this is not a universal solution of soil problems. Adequate quantities of manure frequently are not available, and, furthermore, manure produced on one soil and applied to another, still leaves open a question of fertilization of the soil from which the nutrients contained in the manure were withdrawn. It cannot be denied that under modern agricultural conditions, commercial fertilizers of one type or another must ultimately play an indispensable rôle, subject to such limitations as this circular attempts to describe.

FERTILIZATION AND QUALITY OF THE CROP

Much discussion has taken place concerning the possible influence of potassium or phosphate fertilization on quality of crop as distinct from yield. It seems evident that the quality of crops may be influenced by fertilizer applications under some soil and climatic conditions. The improvement or change of quality occurs primarily in soils which are initially very deficient in ability to supply one or more nutrient elements. Many of the reports dealing with the effects of fertilizers on quality of crops are based on experiments carried out under soil and climatic conditions different from those found in most parts of California.

Numerous observations have been made indicating that fertilizers applied to deficient soils may alter the rate of growth or time of maturity of various crops. For example, phosphate, when applied to soils deficient only in this nutrient, may accelerate root development and promote tillering and grain formation in cereals. With plants of this type, the presence of adequate amounts of available phosphate in the soil during the early stages of plant growth seems to be very important. The addition of potassium to a soil deficient in available potassium tends to produce plumper seed in the case of cereals. None of the effects just mentioned will be observed if the potassium or phosphate already present in the soil is sufficiently available.

With fruit trees, it is exceedingly difficult to obtain convincing results concerning quality of fruit when both the fertilized and unfertilized trees produce healthy foliage. Most reports by investigators in California have been negative or inconclusive, although much further study of this question is needed. Yield or quality, or both, may be affected by soil conditions producing disease, but the principal cases so far observed in California (little-leaf, mottle-leaf, exanthema, etc.), are not related to ordinary nutrient deficiencies but to more obscure causes. In certain restricted districts, deficiency of potassium is one factor in a disease of prune trees.[7]

Field observations have been cited by investigators in various parts of the world, which are believed to show that an inadequate supply of potassium renders plants less resistant to the attack of certain microörganisms, especially fungi. The possible relation of fertilization with phosphate or potassium to some kinds of plant diseases is a subject of great interest. Unfortunately, the investigational work is extremely complicated, and we do not now have any adequate working knowledge. It is not unreason-

[7] For discussion of fertilization of fruit trees see: Proebsting, E. L. Fertilizing deciduous fruit trees in California. California Agr. Exp. Sta. Bul. 610:1–29. 1937.

able to suppose that with some, but by no means all, diseases produced by organisms, plants are more likely to suffer serious injury when in a state of malnutrition. A marked deficiency of an essential element leads to an abnormal change in the organic composition of plant tissues, and this may make the plant more susceptible to attack by microörganisms or by insects. On the other hand, excessive use of nitrogen may produce a succulent plant of low resistance to certain diseases.

ACID AND ALKALINE SOILS

Many inquiries are made concerning the acidity or alkalinity of soils. All soils have either neutral, acid, or alkaline reaction in the soil moisture. This reaction is usually subject to certain fluctuations, according to moisture conditions, amount of carbon dioxide present, and other factors. By a neutral reaction is meant one which is exactly the same as that of absolutely pure water, used as a standard. The degrees of acidity or alkalinity are designated by the symbol pH.[8] Markedly acid soils are common in some regions, but they are comparatively rare in California. Soils of this character may be found in those areas of the state having a high rainfall. Highly alkaline soils also occur, but a discussion of these soils would make necessary a consideration of "alkali" conditions, which are discussed in other publications of the Station. The reaction of a soil is subject to change resulting from the action of substances added to the soil. Thus, sulfate of ammonia may tend to increase acidity, and nitrate of soda to lessen acidity, or to increase alkalinity. Sulfur tends to increase acidity or to decrease alkalinity. These changes are associated with biological activities of microörganisms or of the plants. Lime decreases soil acidity by chemical reaction with the soil. It is difficult by the use of ordinary fertilizers to bring about appreciable changes in the reaction of a soil within a limited period of time, unless the soil is of a light or sandy character and has a low resistance to change of reaction through the addition of acid or alkaline materials. It should not be assumed without special information concerning the character of the soil that lime or other substances are required to change the reaction.

With most plants of agricultural interest, a considerable latitude in soil reaction is consistent with good growth. An acid soil is not necessarily unproductive. For example, certain rather acid peat soils, when properly fertilized, are very productive. The reaction or "pH" of a soil is merely *one* factor influencing growth, and the determination of this

[8] With this system, pH 7 means a neutral reaction; values below 7 indicate acidity, and values above 7, alkalinity. A soil of pH 5 is decidedly acid; one of pH 9, decidedly alkaline. A great many soils in this state have reactions not far from the neutral point.

value, important as it is at times, seldom or never should be relied on as a guide to understanding soil conditions, without a suitable knowledge of other factors interrelated with the reaction. The exchangeable bases held by soil colloids, as related to soil acidity or alkalinity, are of great significance. Also the reaction of the soil influences the availability of elements like iron and manganese.

SOIL ANALYSIS

It is hoped that this presentation of the complexity of soil problems has made it clear that routine chemical analyses alone cannot often determine the adaptability of soils to crops, or the best method of fertilization. It is true that special investigations on soils, and the understanding of general principles, cannot progress without the use of chemical methods, but really adequate studies are costly. They can be carried out by the Experiment Station only in selected cases, to obtain knowledge of general relations, or to aid in the planning or interpretation of field experiments. The validity of any interpretation of chemical data must rest finally on the results of experiments with plants. Even if there were now available assured methods of obtaining and interpreting chemical data on soils in terms of crop growth, there would still remain the question of securing representative samples of soil for examination. The most uniform field in appearance may, in fact, contain numerous soil variations, so that it is extremely difficult to obtain samples which reflect an average condition. In addition, there arises the question of the relative importance of samples of soil taken from different depths, which would vary with the rooting habit of the crop, physical and chemical character of the different soil horizons, and irrigation practice.

If it be desired to consider the examination of soils by the method of water extraction, it should be recalled that the soil moisture does not have a constant composition. In fact, the composition may vary from day to day. The rapid growth of certain crops may bring about a temporary depletion of substances dissolved in the soil moisture, even with the most fertile soils. Therefore, if methods of this type are to be employed, it is necessary to recognize that different results may be obtained when samples are taken at different times of the year. The investigations of recent years emphasize the necessity of including studies on the solid portion of the soil, in order to understand its ability to continue supplying nutrients to the soil moisture. The supply of available nitrogen depends on seasonal microbiological activities which cannot be appraised by a single simple test.

Occasionally soils are found on which comparatively simple chemical

tests may strongly suggest a deficiency of potassium or phosphate, but such soils are often extreme enough in character so that the general nature of the deficiency is already recognized by practical observations. Any possible future development tending toward a more general application of chemical tests to soils must be the result of comprehensive controlled experiments with different crops, as well as of a more critical study of field experience than it has yet been possible to make in most parts of the state. The great diversity of crops, soils, and climatic conditions in California make the problem of interpreting chemical tests on soils far more complex than in those states in which routine chemical tests are widely employed. Nevertheless, a careful survey of soils is being made with reference to the application of recently devised chemical and biological tests. Special attention is directed to extending our knowledge of potassium and phosphate availability in California soils. Eventually the results of field experiments should clear the significance, or lack of significance, of the tests.

Soil and plants are altogether too complex to permit of any easy or quick method of determining the best methods of soil treatment. There must be a patient accumulation of knowledge gained in several ways: (a) by continued investigation of basic relations which enter into soil problems everywhere; (b) by further practical observation and experience; (c) by very carefully conducted and long-continued pot experiments and local field tests or experiments, preceded or accompanied when necessary by special chemical and physiological studies. Increasing attention is being given by the Experiment Station to studies of soil productivity in relation to the use of fertilizers. Systematic pot experiments on the relative productivity of important types of soils have been inaugurated.

Immediate practical steps to be taken cannot be decided upon without reference to local conditions, and none of the statements contained in this circular should be construed as a specific recommendation for any kind of soil treatment. Those who desire to avail themselves of the services of the College of Agriculture should consult the farm advisor if there is one in the county. This representative of the institution has available to him the information gained in the investigations of the Experiment Station and can be helpful in applying it to local conditions.

The College of Agriculture of the University of California is often able to help in the solving of special soil problems. Inquiries regarding this service may be addressed to the county farm advisor in the county where the property is located or to the Agricultural Experiment Station, University of California, Berkeley.

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